

MOLTEN CAUSTIC LEACHING AT LOW CAUSTIC/COAL RATIOS

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KEYWORDS: Molten caustic leaching, coal desulfurization, sulfide coal interaction

INTRODUCTION

Molten caustic leaching (MCL) of coal has been studied under a variety of conditions, many of which studies have been conducted using a large excess of liquid caustic (3:1 caustic/coal or higher) so that, with stirring, coal is suspended in it. This provides a uniform temperature throughout the mixture and is preferred for chemical research. Some development studies have made use of lower ratios of caustic, such as TRW's 20 lb/hr kiln work by Meyers^{1,2}, and the studies of Chriswell and Markuszewski at Ames Laboratory³ and by Kusakabe in Japan⁴. In the Japanese work, Illinois #6 coal was impregnated with mixed KOH and NaOH (52:48 parts by weight) from an aqueous solution to give 51 wt% caustic on the dry coal which after MCL treating, 2 hr at 375°C, produced a coal having only 0.50 wt% total sulfur. Less caustic should help in reducing the cost of an MCL process. Moreover, at high ratios much more caustic is present than necessary to form salts of sulfur and mineral matter in coal. We have calculated that to form the sodium salts of the sulfur and mineral matter present in an 8% ash, 4.2% sulfur, Pittsburgh #8 coal would take about 0.15 parts of sodium hydroxide for one part of dry coal. This does not take into account carbonate formation nor cleavage of carbon-oxygen bonds which also can occur.

The work at Ames National Laboratories has shown that a 2.0:1 ratio can be very effective for desulfurization but that lower ratios tend to give less conversion of sulfur. This group has also demonstrated improved conversion can be obtained by heating in two stages, first to an intermediate temperature, e.g., 250° for an hour, followed by a second-stage, rapidly increasing the temperature to 390°C and immediately cooling, to give desulfurization equivalent to two hours at 390°C. A recent paper reported by Akhtar and Chriswell⁵ reveals that treating Illinois #6 coal in boiling water for one hour, makes the coal more reactive in a subsequent MCL treating step. TRW's work demonstrated production of low sulfur coal in continuous flow MCL using standard process equipment, such as, a kiln reactor, filters, and centrifuges made from caustic- and acid-resistant materials. Most of their tests were conducted above 2.0:1 ratio. They have also found a means of counter-current water washing that does not require the usual acidification step².

Because the use of less caustic could offer cost advantages, PCR Technologies prepared a Small Business Innovation Research (SBIR) proposal for studying MCL at low caustic/coal ratios which resulted in a grant awarded by the US Department of Energy⁶. The objectives of this work have been to examine MCL under conditions that could be used for commercial chemical coal cleaning. This has meant using reasonably low levels of acid water and caustic. Tests have been made using coal from three different seams: western Kentucky #9, Illinois #6, and a low- and a high-sulfur Pittsburgh #8. Semiannual reports issued from the grant have shown that significant amounts of desulfurization and demineralization occur at ratios of 0.5:1 to 2:1 but, at most conditions used, desulfurization was not sufficient to meet New Source Performance Standards (NSPS) for the year 2000. NSPS will require certain coal burning facilities to emit no more than 1.2 lbs SO₂/MMBtu by the year 2000. We have found some single-step sets of conditions at 0.75 ratio with which KY #9 coal and a low-sulfur Pgh #8 coal did meet the 1995 NSPS goal of 2.5 lbs SO₂/MMBtu. However, using 2:1 caustic/coal ratio, the 1.2 lbs SO₂/MMBtu level was met with the same two coals. Sulfur removal attained at low ratios in single-step and in two-step MCL tests are compared and experiments showing how the desulfurization level appears to be limited by the presence of sulfide are addressed in this paper.

EXPERIMENTAL

Most of the experiments described were conducted in an annealed stainless steel, 1-3/8" I.D. pipe reactor containing a 4-3/4" stirrer

blade having a width nearly the diameter of the pipe. During tests, the stirrer was rotated by an induction motor at 5.5 rpm and the reactor held at an angle of 30° from horizontal. Nitrogen gas was passed slowly through the reactor, at atmospheric pressure, while heating the reactor in a hinged furnace. A thermowell passed through a bottom closure and acted as a bearing for the bottom of the stirrer shaft which allowed the MCL reaction temperature to be monitored.

Most often, test conditions were randomized to avoid any sequence or time bias. In a typical test, 18g of 14 mesh x 0 coal and an amount of NaOH beads (20-40 mesh) to give the desired caustic/coal ratio were poured into the reactor and the top screwed in place. The furnace was heated rapidly while the reaction mixture was stirred constantly. Reaction temperatures of 350° to 430°C were reached in about 65 to 85 minutes respectively. The reaction period time was begun as the internal temperature reached 3°C below test temperature and ended when the temperature dropped 3°C below that value. Usually internal temperatures were held within +/-3°C of this value. Cooling was begun in anticipation of the end of the reaction period by turning off the heat, opening the split-hinged furnace, and turning a fan on. The cool-down was about twice as fast as heat-up time. The initial gallon-size samples of high- and low-sulfur Pgh #8 and western KY #9 coals were received from TRW and are coals TRW used in their integrated kiln test program. The IL #6 coal, IBC-101, was received from the Illinois State Geological Survey. A second, larger sample of high-sulfur Pgh #8 coal was obtained through Tra-Det Inc., Wheeling WV. Sodium hydroxide beads (20 x 40 mesh) were used as the source of caustic for these MCL tests. In a few tests, sulfide was added to a caustic/coal mixture, in which case the sulfur source was either Fisher 21.2% aqueous ammonium sulfide solution (9.97 wt% sulfur) or Aldrich 98% sodium sulfide nonahydrate, ACS reagent.

A few larger scale runs were made using a Parr Instrument Co. 6-liter stainless steel stirred reactor so that a partially or completely desulfurized product could be made from 400 to 2000g of the coal. Reactants, including some water, were loaded into the reactor and pressure tested using nitrogen. Tests were conducted either at a fixed pressure, e.g., 400 psig, using a back-pressure regulator with slow flow of nitrogen through the regulator or the reactor was sealed containing at least 30 psig (nitrogen) and allowed to attain whatever pressure occurred at run conditions. For depyriting runs at 250°C, water vapor pressure accounted for most of the pressure observed. Products from the Parr reactor were used as feed for second-stage, atmospheric pressure tests in the pipe reactor.

Products were generally worked up by digesting the cooled mixture of caustic/coal in an amount of hot water equal to four times the weight of coal, filtering the coal and rinsing with up to two weights of hot water. The coal was acidified while dispersed in 2 to 4 weights of water by adding dilute HCl until a pH of 1.2 was maintained for five minutes. (Sulfuric acid would likely be used commercially.) The slurry was then heated to 90°C for 20 minutes with stirring. The hot slurry was filtered and rinsed with two weights of hot water. Moist coal samples were dried at 105° to 110°C.

Coal analyses were conducted by Standard Laboratories, Inc., Cresson, PA. Alkaline wash filtrates were titrated at PCR Technologies to determine total alkalinity (to pH 4.0) and free NaOH (to pH 8.35) in the presence of excess BaCl₂.

RESULTS AND DISCUSSION

High-sulfur Pgh #8 coal was found to be the most resistant to MCL of the three coal seams selected for our study and was chosen for our initial experiments. Over eighty tests were made with this coal in Phase I and II of our grant. A low-sulfur Pgh #8 was also tested in six runs, twenty-one tests were made with IL #6 coal, and over fifty tests with western KY #9 coal. Data (in some cases averages of duplicate runs) for tests at both 0.75:1 and 2:1 caustic/coal ratios are shown in Table 1. Our goal was to obtain a low-sulfur product that would emit 1.2 lbs SO₂/MMBtu or less on combustion. Even a cursory scan of Table 1 shows that few tests actually achieved this goal and then only from low-sulfur Pgh #8 and KY #9 coals treated at 2.0:1 caustic/coal ratio and temperatures of 390°C or higher.

In MCL treating, pyritic sulfur is much more reactive than organic sulfur and can be removed at a temperature about 100°C lower than is necessary for desulfurizing organic sulfur structures in coal. Thus, effective MCL treating becomes a matter of removing of organic sulfur in the quest for acceptable NSPS coal product. The problem, at first glance might seem to be due to the slow desulfurization reaction rate of organic sulfur in coal. However, longer reaction time often had little effect on desulfurization with these coals. This was more noticeable for those tests using 0.75:1 caustic/coal than 2:1. This could be caused by some organic sulfur structures in coal being more resistant to reaction than others, by steric hindrance of some sulfur moieties, by parts of the solid coal not being in contact with the caustic, by the caustic reacting with coal constituents that used up the caustic, or by a reversible reaction in which a concentration of by-product builds up and prevents further desulfurization at that temperature. Except for high-sulfur Pgh #8, tests at 2:1 ratio definitely caused more desulfurization than did those at 0.75:1. Product from 0.75 ratio runs were obviously wetted and formed solid masses on cooling. Therefore, lower conversion levels should not be due to impervious coal or steric hindrance since higher ratios of caustic/coal increased sulfur removal. Titrations of the water wash filtrates from tests showed that some weak acid salts were formed, but 32 to 80 wt% of free NaOH was still available for tests at 0.75:1 and 55 to 81 wt% at 2:1 ratio. There was ample unreacted caustic remaining to continue the desulfurization reaction. Poor reactivity could best be attributed to more resistant sulfur bonds after the facile carbon-sulfur bonds had reacted or to some form of reversible reaction.

Therefore, an investigation into sulfide as a possible by-product that could interfere with coal desulfurization by a reversible or retrograde reaction was begun. Pyrite in MCL reaction forms sulfide and can quickly build up in the caustic before organic sulfur begins to react. This sulfide concentration effect would be much greater with low ratio tests. Therefore, the first attempt to test whether sulfide in the caustic can reduce the desulfurization of coal was to remove the pyrite from KY#9 coal in a mild MCL reaction and then treat that product in a second-step MCL treat. Both reactions were made with 0.75:1 ratio caustic/coal; the first step was run at 320°C for 50 minutes and the second step at 390°C for only two minutes. Table 2 compares the results with other tests made for various reaction times at 390°C. The first step or "pretreat" test removed 88% of the pyritic sulfur and also about 12% of the organic sulfur. The second step test removed 50% of the remaining organic sulfur and nearly met NSPS year 2000 criteria. For comparison at the same temperature, a 2-minute test removed 34% of organic sulfur and the best level attained, at 50 minutes, removed only 40%. In another approach to investigate the influence of sulfide, hydrogen sulfide was added to a 2:1 ratio of caustic and coal in an amount equivalent to 4-times the weight of total sulfur in KY #9 coal. The H₂S gas was generated from a weighed amount of (NH₄)₂S solution and carried by nitrogen flow into the reactor while holding the MCL reactor charge at 170° to 180°C. Immediately thereafter, the MCL test was run at 390°C. The result was that, although pyrite was effectively removed from the coal, the organic sulfur content remained essentially unchanged. The presence of this much sulfide in the caustic clearly prevented desulfurization of organic sulfur. A hypothesis that MCL desulfurization can be severely affected by the concentration of sulfide in caustic began to unfold.

Another coal, the low-sulfur Pgh #8, was used for a second series of tests to see if it was similarly sensitive to a change in sulfide concentration. Table 3 repeats a few test results of Table 1 for comparison with 2-step MCL treating. In the "pretreat" step, coal was depyrited in the 6-liter reactor using 0.5:1 caustic/coal and enough water to give a 38% solution of the NaOH. Depyriting was conducted for 25 minutes at 250°C and produced a very low pyrite coal with an organic sulfur content elevated about 25% to 1.26 wt%. This depyrited, low-sulfur coal was then used in second-step MCL reactions in the small reactor. Tests were made at 0.25, 0.50, and 0.75 ratios for 25 and 100 minute tests at 390°C. With as little as 0.25 ratio, the NSPS 2000 sulfur dioxide limit was almost achieved and the higher ratio tests were well below the NSPS limit by 25 to 65 %. Two-step MCL treating was necessary to produce NSPS compliance coal when using 0.75 and lower ratios, but it is apparent that there are coals of

moderate to low sulfur content which would respond well to MCL treating at low ratios.

The original high-sulfur Pgh #8 coal was depleted in laboratory tests and a large, fresh sample was needed for larger-scale tests. The original sample had a combined sulfate and pyrite content indicating it had contained 1.57 wt% pyritic sulfur, when fresh, and 2.76 wt% organic sulfur. Our second high-sulfur Pgh #8 sample, obtained from the same mine by Tra-Det, Inc., contained 1.95 wt% pyritic sulfur, 0.05 wt% sulfate sulfur, and 2.45 wt% organic sulfur. In Table 4, data showing a comparison of MCL tests at 2.00:1 ratio for the two coal samples are presented. The Tra-Det sample was somewhat less resistant to treating and met the 1995 NSPS but not that for 2000. Shown next are two-step results from depyriting high-sulfur Pgh #8 coal in the 6-liter reactor and the use of this product in second-step MCL tests. The depyriting was conducted using a 0.62 ratio for 25 minutes at 250°C, during which the reactor was maintained at a pressure of 400 psig. Pyrite conversion was 95% and organic sulfur content increased about 20% when loss of mineral matter, volatiles and pyrite were considered. Using the depyrited, high organic sulfur product as a coal feed, second-step, 25-minute MCL tests were made at 0.25, 0.75 and 2.00 ratios and 390 to 430°C reaction temperatures with interesting results. The 0.25:1 ratio test desulfurized 36% of the organic sulfur but still had more than twice the $SO_2/MBBtu$ level desired. However, desulfurization with 0.75:1 ratio at 410° and 430°C produced compliance coal product and the 2.00:1 ratio tests, as would be expected, gave even lower sulfur levels at 390°, 410° and 430°C. Two-step, low-ratio treating offers promise for achieving NSPS compliance product even from a high-sulfur coal.

In another experiment, excellent chemical cleaning of Pgh #8 was obtained using a very high ratio, 5.00:1, for 25 minutes at 400°C. However, the following test shows that sulfur removal is reversible when treated in the presence of NaOH and sulfide as in a MCL test. The clean coal contained only 0.73 wt% total sulfur, of which 0.69 wt% was organic. This clean coal was mixed with both NaOH (1.67:1) and Na_2S (0.50:1) and treated for 25 minutes at 390°C. The amount of Na_2S added provided 3.69 g S^{2-} , several times the total sulfur content of untreated Pgh #8 feed coal and demonstrates that sulfide can cause a higher sulfur product to form. The result was that organic sulfur in the sulfided MCL product increased to 1.42 wt%, about twice the amount of organic sulfur in the cleaned coal. The previously clean coal, 0.97 lbs $SO_2/MBBtu$, now would produce 2.03 lbs $SO_2/MBBtu$ on combustion.

If sulfide concentration builds-up sufficiently, a retrograde sulfurizing reaction can occur that will limit or possibly slowly increase the organic sulfur content in coal. Whether the same type of organic sulfur compounds form as are desulfurized has not been determined. Studies of the reactions of organosulfur compounds thought to represent structures in coal^{7,8}, such as thiophene, benzothiophene or dibenzothiophene have not been approached as reversible reactions. Often desulfurized products were obtained that also lacked an oxygen. Once that has happened, it is less likely a reaction to incorporate sulfur in a hydrocarbon would occur than it would be to have an exchange between phenolic oxygen and thiophenolic sulfur in the presence of molten caustic. We suspect that the latter type reactions are at play and that some of the phenolics may come from hydrolysis of furan structures in coal.

With coals containing less than 6 wt% sulfur, it is not likely that sulfide could build-up to a high concentration at high ratios so the reverse reaction might not be noticed. However, at low caustic/coal ratios, especially when the coal contains over 2 wt% total sulfur, a desulfurization limitation may occur well before NSPS criteria are reached.

We believe that MCL desulfurization of coal is sensitive to the molar concentration of sulfide ion in the caustic solution. If the molar concentration is low enough, desulfurization can proceed rapidly and only a few minutes, not hours, of MCL reaction time is necessary at temperatures above 370°C. If the sulfide concentration is high, desulfurization cannot proceed regardless if the time or temperature would otherwise be practical for MCL treating. For coals having much pyrite, a low temperature depyriting step followed by a MCL reaction

to remove the requisite amount of residual organic sulfur can achieve compliance coal quality. By considering carefully the amount of sulfur to be removed and the reactivity of the coal, low ratios of caustic/coal could in many instances be used in place of much larger amounts of caustic.

SUMMARY

Conditions have been presented showing MCL desulfurization of coals from three coal seams at low caustic/coal ratios. Ratios at 2.00:1 were successfully used in single-step MCL reactions for treating of a 2 wt% sulfur Pgh #8 coal and a 3.4 wt% sulfur western KY #9 coal to achieve NSPS 2000 compliance product, 1.2 lbs SO₂/MMBtu. Coals having over 4 wt% sulfur were not successfully treated under the same conditions, but a 4.4 wt% sulfur Pgh #8 coal in a two-step reaction at 0.75:1 ratio of caustic/coal did achieve this goal. Several examples of two-step treating have been presented in which the first step is a lower temperature reaction to remove pyrite.

Experiments have demonstrated that desulfurization is sensitive to the presence of sulfide in caustic during MCL treating. Reducing sulfide concentration by depyriting a coal before MCL treating can allow the second-stage MCL treat to be effective even at quite low caustic/coal ratios. Introduction of sulfide into the MCL caustic, can retard desulfurization or at higher levels actually increase sulfur content. The increase is measured as organic sulfur.

ACKNOWLEDGEMENT

We gratefully acknowledge financial support for this study by the Department of Energy, Office of Energy Research for the SBIR grant, DE-FG03-90ER80957.

We thank The TRW company for providing us with samples of high-sulfur and low-sulfur Pgh #8 and western KY #9 coals they used in their kiln studies for DOE contract DE-AC22-86PC91257.

Finally we thank John Spotts and Robert Pawlak for conducting a number of the MCL reactions reported.

DISCLAIMER

References to any specific commercial process, product or service is to facilitate understanding and is not meant to imply endorsement or favoring by PCR Technologies or the US Department of Energy.

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Table 1
SMALL REACTOR MCL DESULFURIZATION EXPERIMENTS
SINGLE-STEP REACTIONS

---Run Conditions---			--Analyses, mf basis--			---Sulfur Forms, mf---		
NaOH/Coal	Temp.	Time	Sulfur	Ht Value	SO ₂	Pyritic	Sulfate	Organic
Ratio	C	min	wt%	Btu/lb	lbs/MMBtu	wt%	wt%	wt%
A: High-Sulfur Pgh#8 Coal			4.33	12521	6.91	1.07	0.50	2.76
0.75	370	50	1.89	13535	2.79	0.14	0.32	1.43
0.75	390	150	1.87	14221	2.63	0.02	0.05	1.80
0.75	410	50	2.16	13973	3.09	0.05	0.07	2.04
0.75	430	25	1.92	13205	2.91	0.06	0.31	1.55
0.75	430	100	1.73	13699	2.52	0.07	0.13	1.52
0.75	470	50	1.25	13081	1.91	0.18	0.29	0.79
2.00	350	50	2.65	14157	3.74	0.05	0.06	2.54
2.00	370	50	2.43	14156	3.43	0.05	0.08	2.30
2.00	390	50	2.43	14013	3.47	0.07	0.11	2.26
2.00	390	150	2.06	13980	2.94	0.04	0.20	1.82
2.00	410	50	2.43	13569	3.57	0.04	0.25	2.14
2.00	430	25	2.20	13572	3.24	0.06	0.20	1.93
2.00	430	50	2.54	13184	3.85	0.05	0.35	2.14
B: Low-Sulfur Pgh#8 Coal			2.03	13844	2.93	1.02	0.01	1.01
0.75	390	50	1.07	14082	1.52	0.11	0.03	0.93
0.75	430	*2	1.09	14201	1.53	0.08	0.04	0.97
0.75	430	25	1.03	13900	1.48	0.05	0.05	0.93
2.00	390	50	0.62	14464	0.86	0.04	0.01	0.57
2.00	430	*2	0.53	14446	0.73	0.03	0.00	0.49
2.00	430	25	0.26	14101	0.37	0.02	0.01	0.23
C: IL#6 Coal			4.35	12485	6.97	0.90	0.11	3.34
0.75	350	50	2.77	13500	4.10	0.16	0.10	2.50
0.75	370	50	1.99	13120	3.03	0.10	0.18	1.71
0.75	390	*5	1.82	13935	2.61	0.09	0.05	1.68
0.75	390	50	1.63	13336	2.44	0.06	0.16	1.41
0.75	390	*100	1.71	13711	2.49	0.07	0.06	1.58
0.75	410	50	1.64	13004	2.52	0.04	0.27	1.33
0.75	430	50	1.50	13150	2.28	0.07	0.24	1.19
2.00	350	50	2.87	13764	4.17	0.10	0.05	2.72
2.00	370	50	1.71	13618	2.51	0.03	0.09	1.59
2.00	390	50	1.93	13517	2.85	0.05	0.09	1.79
2.00	410	50	1.00	13308	1.50	0.01	0.21	0.78
2.00	430	50	1.43	13254	2.16	0.07	0.25	1.11
D: W.KY#9 Coal			3.39	12730	5.32	0.90	0.50	2.00
0.75	370	2	1.87	14071	2.66	0.24	0.02	1.62
0.75	390	2	1.48	14055	2.10	0.12	0.04	1.33
0.75	390	25	1.36	13416	2.02	0.06	0.09	1.21
0.75	390	100	1.40	13697	2.04	0.07	0.07	1.26
0.75	410	2	1.42	13975	2.03	0.11	0.04	1.27
0.75	430	2	1.38	13773	2.00	0.08	0.06	1.25
2.00	370	2	1.49	14138	2.11	0.10	0.02	1.38
2.00	390	2	1.09	14216	1.53	0.05	0.02	1.02
2.00	390	100	0.43	12561	0.68	0.04	0.08	0.31
2.00	410	2	0.74	14175	1.04	0.04	0.03	0.67
2.00	430	2	0.64	13803	0.92	0.06	0.07	0.52
2.00	430	25	0.65	13396	0.96	0.04	0.14	0.47

* Coal pretreated 50 minutes at 320C.

TABLE 2
MCL EXPERIMENTS WITH KENTUCKY #9 COAL
EFFECTS OF REMOVING OR ADDING SULFIDE

----Run Conditions----			--Analyses, mf basis--			---Sulfur Forms, mf---		
NaOH/Coal	Temp.	Time	Sulfur	Ht Value	SO ₂	Pyritic	Sulfate	Organic
Ratio	C	min	wt%	Btu/lb	lbs/MMBtu	wt%	wt%	wt%
			3.39	12730	5.32	0.90	0.50	2.00
Single-Step Tests								
0.75	390	2	1.48	14055	2.10	0.12	0.04	1.33
0.75	390	25	1.36	13408	2.02	0.06	0.09	1.21
0.75	390	100	1.40	13697	2:04	0.07	0.07	1.26
Two-Step Test: Step 1 - Removing Sulfide (Mostly Pyrite)								
0.75	320	50	1.91	14190	2.69	0.11	0.04	1.76
Two-Step Test: Step 2 - MCL Treat of Depyrited Coal								
0.75	390	2	0.94	14376	1.31	0.03	0.02	0.89
Single-Step Tests								
2.00	390	2	1.09	14216	1.53	0.05	0.02	1.02
2.00	390	100	0.43	12561	0.68	0.04	0.08	0.31
Single-Step Test - Adding Sulfide to Untreated Coal								
**2.00	390	25	2.14	13853	3.09	0.04	0.11	1.99
** H ₂ S added at 170/180C to give 5.89g Na ₂ S, leaving 29.96g NaOH; Resulting in 1.66:1 NaOH/coal and 0.33:1 Na ₂ S/coal.								

TABLE 3
MCL EXPERIMENTS WITH LOW-SULFUR PITTSBURGH #8 COAL
EFFECTS OF REMOVING OR ADDING SULFIDE

----Run Conditions----			--Analyses, mf basis--			---Sulfur Forms, mf---		
NaOH/Coal	Temp.	Time	Sulfur	Ht Value	SO ₂	Pyritic	Sulfate	Organic
Ratio	C	min	wt%	Btu/lb	lbs/MMBtu	wt%	wt%	wt%
Low-Sulfur Pgh #8			2.03	13844	2.93	1.02	0.01	1.01
Single-Step Tests								
0.75	390	50	1.07	14082	1.52	0.11	0.03	0.93
0.75	430	2	1.09	14201	1.53	0.08	0.04	0.97
0.75	430	25	1.03	13900	1.48	0.05	0.05	0.93
2.00	390	50	0.62	14464	0.86	0.04	0.01	0.57
Two-Step Tests: Step 1 - Removing Sulfide (Pyrite)								
0.50	250	25	1.38	14389	1.92	0.08	0.04	1.26
Two-Step Tests: Step 2 - MCL Treat of Depyrited Coal								
0.25	390	25	0.91	14418	1.26	0.04	0.02	0.86
0.50	390	25	0.59	13234	0.89	0.02	0.03	0.54
0.75	390	25	0.60	14525	0.83	0.02	0.07	0.52
0.75	390	100	0.26	13304	0.42	0.01	0.03	0.24

TABLE 4
MCL EXPERIMENTS WITH HIGH-SULFUR PITTSBURGH #8 COAL
EFFECTS OF REMOVING OR ADDING SULFIDE

----Run Conditions----			--Analyses, mf basis--			---Sulfur Forms, mf---		
NaOH/Coal	Temp.	Time	Sulfur	Ht Value	SO2	Pyritic	Sulfate	Organic
Ratio	C	min	wt%	Btu/lb	lbs/MMBtu	wt%	wt%	wt%
TRW Sample			4.33	12521	6.91	1.07	0.50	2.76
Tra-Det Sample			4.45	13326	6.67	1.95	0.05	2.45
Single-Step Tests - Comparing Two Pgh #8 Samples								
TRW@ 2.00	390	50	2.43	14013	3.47	0.07	0.11	2.26
T-D@ 2.00	390	25	1.83	14391	2.54	0.05	0.05	1.73
TRW@ 2.00	430	25	2.20	13572	3.24	0.06	0.20	1.93
T-D@ 2.00	430	20	1.39	13842	2.01	0.05	0.08	1.26
Tra-Det Sample Used for All Tests Below								
Two-Step Tests: Step 1 - Removing Sulfide (Pyrite)								
0.62	250	25	3.33	13413	4.96	0.09	0.09	3.17
Two-Step Tests: Step 2 - MCL Treat of Depyrited Coal								
0.25	390	25	2.16	14257	3.03	0.03	0.11	2.02
0.75	390	25	1.34	12844	2.08	0.05	0.13	1.16
0.75	410	25	0.79	14028	1.13	0.02	0.10	0.67
0.75	430	25	0.63	13867	0.91	0.03	0.06	0.54
2.00	390	25	0.65	14312	0.91	0.01	0.11	0.54
2.00	410	25	0.34	14109	0.48	0.02	0.08	0.23
2.00	430	25	0.38	13746	0.55	0.04	0.08	0.27
Single-Step Test: High Ratio MCL Treat								
*5.00	400	25	0.73	15066	0.97	0.02	0.01	0.69
Single-Step Test - Adding Sulfide to MCL Cleaned Coal (*)								
1.67	390	25	1.51	14884	2.03	0.03	0.06	1.42
0.50 Na2S								